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On the investigation of photovoltaic output power reduction due to dust accumulation and weather conditions

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ABSTRACT

Certain environmental conditions such as accumulation of dust and change in weather conditions affect the amount of solar radiation received by photovoltaic (PV) panel surfaces and thus have a significant effect on panel efficiency. This study conducted an experimental investigation in Surabaya, Indonesia, on the effect of these factors on output PV power reduction from the surface of a PV module. The module was exposed to outside weather conditions and connected to a measurement system developed using a rule-based model to identify different environmental conditions. The rule-based model, a clear sky solar irradiance model that included solar position, and a PV temperature model were then used to estimate the PV output power, and tests were also conducted using an ARM Cortex-M4 microcontroller STM32F407 as a standalone digital controller equipped with voltage, current, temperature, and humidity sensors to measure real time PV output power. In this system, humidity was monitored to identify dusty, cloudy, and rainy conditions. Validated test results demonstrate that the prediction error of PV power output based on the model is 3.6% compared to field measurements under clean surface conditions. The effects of dust accumulation and weather conditions on PV panel power output were then analyzed after one to four weeks of exposure. Results revealed that two weeks of dust accumulation caused a PV power output reduction of 10.8% in an average relative humidity of 52.24%. Results of the experiment under rainy conditions revealed a decrease in PV output power of more than 40% in average relative humidity of 76.32%, and a decrease in output power during cloudy conditions of more than 45% in an average relative humidity of 60.45% was observed. This study reveals that local environmental conditions, i.e., dust, rain, and partial cloud, significantly reduce PV power output.

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1. Introduction

Global developments in the use of solar energy have increased over the last decade. However, although the generation of power using solar PV modules is a major renewable energy source, the amount of power output is greatly influenced by environmental conditions such as solar radiation, wind speed and direction, ambient temperature, humidity, and atmospheric dust. In solar PV applications, the total amount of solar radiation received by the surface of a PV module essentially depends on its orientation and local climate conditions, and although the maximum power point tracking (MPPT) algorithm is applied to determine the maximum power output from a PV module, it is unable to operate adequately if dust is deposited on the surface of the PV module [1,2].

Two studies were conducted to investigate the effects of accumulation and physical properties of dust on the performance of PV cells. In the first study, an experimental investigation of the dust accumulation effect on the fill factor, output power, and short circuit current of PV cells was conducted using known materials that were uniformly spread over the PV cells; results showed that the PV cells deteriorated significantly due to the accumulation of dust. In the second study, experimental investigations were conducted using five different physical properties of dust; results showed that finer particles caused greater deterioration in the performance of PV cells than coarser particles. Both studies were conducted using a solar simulator as the source of light and provide experimental evidence of performance deterioration in relation to the

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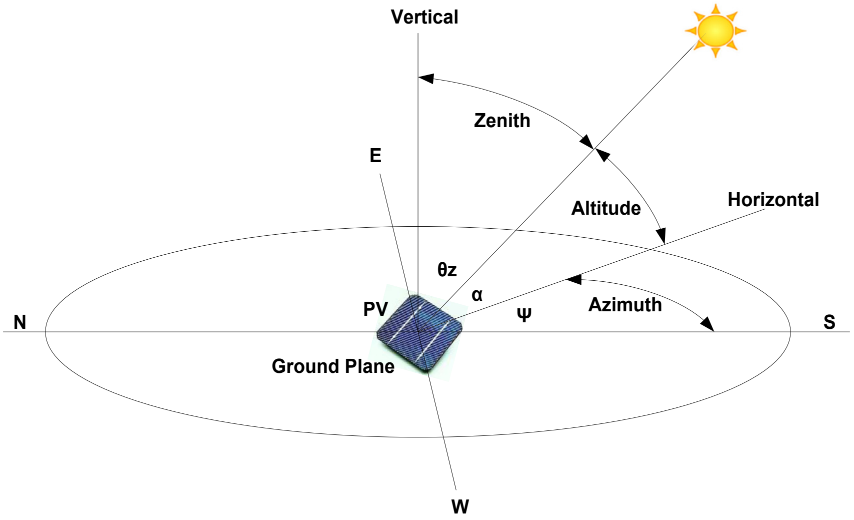


Fig. 1. Coordinate system on Earth's surface.

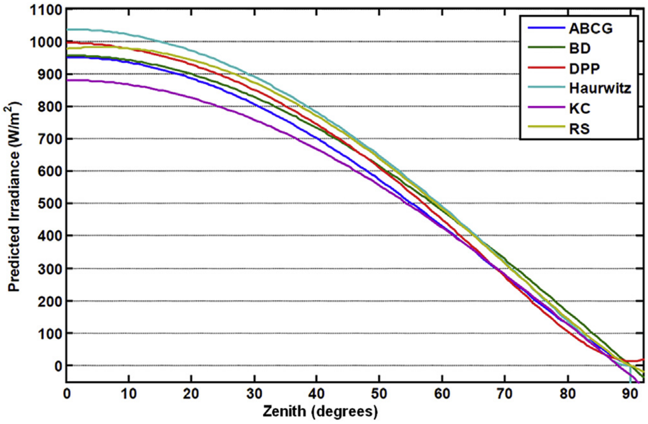


Fig. 2. Comparison of irradiance predictions from several models according to zenith values [26].

accumulation and physical properties of dust [3,4].

Various technical studies using experimental investigations have also been conducted on the impact of dust accumulation and climatic parameters on PV module performance [5–9], and results have indicated that dust concentration, wind direction, wind velocity, air mass, and temperature cause a significant deterioration of PV performance. The researchers in Ref. [10] analyzed PV modules performance based on climatic conditions in desert environment in southern Algeria. In this research, the experimental study was conducted using outdoor measurements of PV modules over an exposure period of 10 years, without specifically identifying particular weather conditions. It is of note that semi-arid and desert regions of the world have high solar intensity but also a large quantity of airborne dust, and large-scale PV plants are commonly located in such regions [11,12].

Furthermore, previous research has also investigated the effects of dust deposition and regional weather conditions on the efficiency of PV modules in various environments. Studies comparing wet and dry seasons have shown that during a long dry season dust deposition can cause a reduction in power output of as much as 20% [13], while in Malaysia it can reach 50% [14], and in Senegal losses range from 18% to 78% [15]. It has also been determined that dust accumulation on PV panels due to a coating of sand in dry regions may decrease PV power by up to 25%, and that if the PV surface is not being cleaned for more than six months losses can reach 50% [16–21].

Ghazi and Ip (2014) investigated the deterioration in PV panel efficiency due to weather conditions in Brighton, UK, in relation to the deposition of solid particles. Results of laboratory experimental simulations using outdoor glass units showed that a small amount of fine particles caused a reduction in light transmittance of 11%. Outdoor field measurement results revealed that the largest negative impacts on the performance of PV panels were related to weather conditions, particularly snow and rain, and the small impact of dust deposits caused by the regional weather [22].

Recent studies conducted experimental investigations on the effect of dust deposition on PV panels in a desert environment. The authors investigated variations in PV module performance during normal days and during dust storm conditions in Iraq. In their experiments, a solar simulator was used to expose dusty and clean modules to a constant level of radiation and temperature with the aim of analyzing the output power and short circuit current. The dust density and particles on the module were also investigated using an aerosol measuring system on a daily, weekly, and monthly basis. Experimental results showed that the accumulation of dust has a significant effect on the expected PV power output [23,24]. In addition, an earlier study evaluated degradation of the electrical performance of PV modules due to the accumulation of dust in southern Poland, where experimental investigations were performed using crystalline PV modules after a few years of exposure to both natural and artificial dust deposition. Experimental results indicated a linear relationship between reduction in efficiency and the dust deposition density [25].

The problem of reduced PV generated power due to dust and weather conditions necessitates an accurate identification of dust accumulation and regional weather conditions. Therefore, this paper aims to investigate the reduction in PV power output due to dust accumulation and weather conditions in the city of Surabaya, Indonesia. Experimental research is conducted to identify weather conditions and the accumulation of dust on the surface of a PV module using a measurement system that was developed based on a simple rule-based model, and solar irradiance and temperature models. Validation results show that field measurement data are in good agreement with prediction results of PV output power. It is considered that the results of this research can be used in the

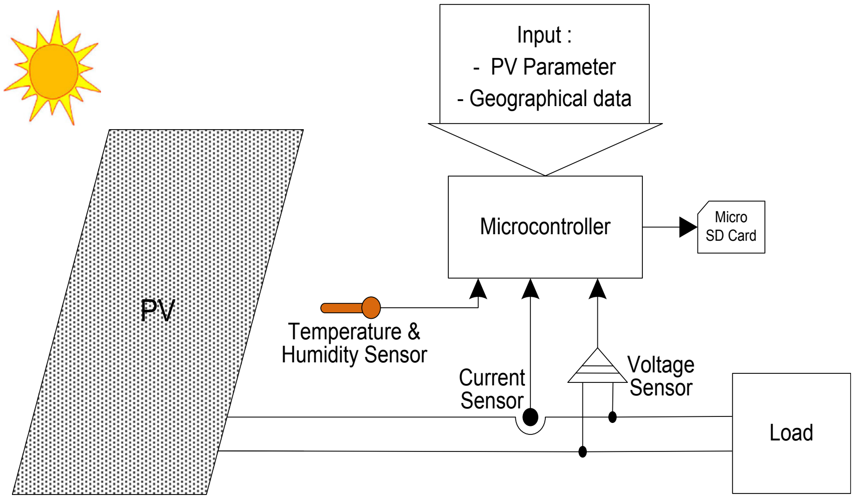
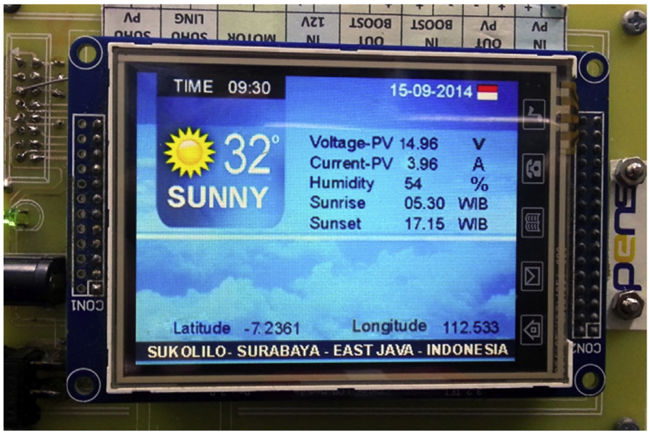


Fig. 3. Configuration of system for monitoring weather and dust accumulation.


TIME 09:30 15-09-2014

32° SUNNY

Voltage-PV 14.96 V
Current-PV 3.96 A
Humidity 54 %
Sunrise 05.30 WIB
Sunset 17.15 WIB

Latitude -7.2361 Longitude 112.533
SUKOLILO- SURABAYA - EAST JAVA - INDONESIA

Fig. 4. Prototype of PV monitoring system.

development of an effective and efficient cleaning system and associated procedure.

2. PV modeling

To determine the effect that dust has on the surface of a PV module, it is first necessary to estimate the output power generated by the PV in real time. This can be conducted using common PV models, models of solar position, solar irradiance models, and PV output power to temperature models. In addition, to determine the existence of rain, a rain classification or rain prediction model can be employed.

2.1. Model of solar irradiance under clear sky

Solar radiation reaching the Earth's atmosphere is called extraterrestrial radiation. For each moment, radiation can be calculated using Equation (1) as

$$I_o = I_{sc}\left(1 + 0.033cos\frac{2\pi}{365}\,n\right)cos\theta_z \tag{1}$$

where I_{sc} is the solar constant, 1.367 kW/m^2 with a 1% margin of error, n is the day of the year ranging between 1 and 365, and θ_z represents the zenith angle. Irradiance on a clear day can be calculated using very simple, clear sky models such as the Daneshyar–Paltridge–Proctor model and the Meinel model [26], as in Equation (2),

$$GHI = DNI \times cos\theta_z + Diffuse \tag{2}$$

$$Diffuse = 14.29 + 21.04\left(\frac{2\pi}{2 - \frac{(\theta_z\ \pi)}{180}}\right) \tag{3}$$

$$DNI = I_o \times 0.7^{AM\wedge 0.678} \tag{4}$$

where

$$AM = \frac{1}{cos\theta_z} \tag{5}$$

and GHI represents global horizontal irradiance, DNI represents direct normal irradiance, and θ_z represents the zenith angle. An illustration of the position of the sun relative to the earth (the zenith angle) is shown in Fig. 1.

Using GHI in a model is effective for predicting irradiance and PV power output; a comparison of results of predictions made by several models is shown in Fig. 2.

2.2. Model of PV output power including irradiance and temperature

The relation of PV output power to irradiance and temperature can be determined by Equation (6) [27] as follows,

$$P_{PV} = P_{PV,STC}\ f_{PV}\ f_{temp}\left(\frac{I_T}{I_{T,STC}}\right) \tag{6}$$

where $P_{PV,STC}$ is the PV capacity at standard test conditions (STC) in kW, f_{PV} is the derating factor of PV (%), I_T is the incident of global solar radiation (kW/m^2), $I_{T,STC}$ is irradiation at STC in kW/m^2. In addition, f_{temp} is the derating factor of temperature, which represents a reduction in PV output due to dust on the surface of the panels, wiring losses, shading, aging, and increased temperature that have an influence on PV output deviation. The temperature derating factor is defined as

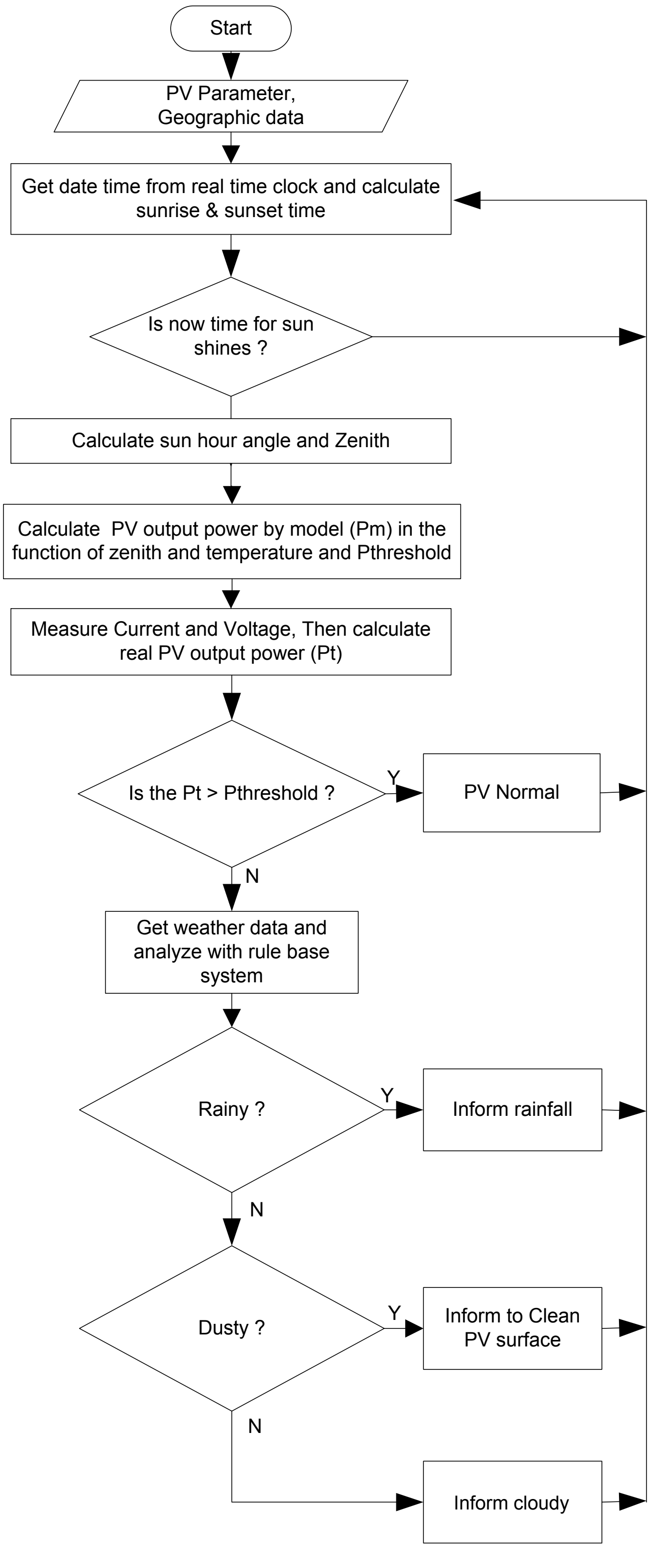

Start
PV Parameter, Geographic data
Get date time from real time clock and calculate sunrise & sunset time
Is now time for sun shines ?
Calculate sun hour angle and Zenith
Calculate PV output power by model (Pm) in the function of zenith and temperature and Pthreshold
Measure Current and Voltage, Then calculate real PV output power (Pt)
Is the Pt > Pthreshold ?
Y
PV Normal
N
Get weather data and analyze with rule base system
Rainy ?
Y
Inform rainfall
N
Dusty ?
Y
Inform to Clean PV surface
N
Inform cloudy

Fig. 5. Flowchart for process of identifying PV power reduction.

Table 1
Determination of environmental conditions.

Condition	Amb. Temp. (°C)	Humidity (%)	PV power
Sunny	$\geq$29.15	$\leq$72.92	Normal
Cloudy	$\leq$29.15	$\leq$72.92	Under threshold
Rainy	$\leq$29.15	$\geq$72.92	Under threshold
Dusty	$\geq$29.15	$\leq$72.92	Under threshold

$$f_{temp} = \left[1 + \alpha_P\left(T_c - T_{c,STC}\right)\right] \tag{7}$$

where α_p represents a temperature coefficient (%/°C), T_c is the temperature of the PV cell for each step of time (°C), and $T_{c,STC}$ is the temperature of the PV cell at STC (25 °C). The temperature of the PV surface, T_c, is equal to the ambient temperature at night time, while it exceeds the ambient temperature during a sunny day. PV surface temperature can be expressed by Equation (8) as

$$T_c = T_a + I_T\left(\frac{T_{c,NOCT} - T_{a,NOCT}}{I_{T,NOCT}}\right)\left(1 - \frac{\eta_c}{\tau\alpha}\right) \tag{8}$$

where T_a is ambient temperature (°C), $T_{c,NOCT}$ is the nominal operating cell temperature (NOCT) in °C unit, $T_{a,NOCT}$ is ambient temperature at a defined NOCT (20 °C), $I_{T,NOCT}$ is solar radiation at the defined NOCT (0.8 kW/m^2), η_c is PV efficiency (%). In addition, $\tau\alpha$ represents PV absorptivity, which is the total absorbed radiation divided by the total radiation striking the PV array surface. It is of note that the PV needs to absorb at least 90% of total radiation.

2.3. *Classification of rain using prediction model*

Relative humidity influences PV output power [28]; when humidity is higher the output power is reduced. However, in this paper relative humidity is not used to determine the reduction of PV output power, but is used to identify rainy conditions. In some research, actual temperature and humidity has been used to predict rainfall using a simple rule-based model, or artificial intelligence [29]. However, in this work temperature and humidity are not used in this respect, but are used for identifying rainfall at a particular time to accurately determine whether dust accumulation or rainy conditions cause the greatest reduction in PV power.

The simple rule-based model used to determine rainfall conditions compares yearly average temperature to humidity under rainy conditions with actual temperature and humidity [30]. This paper uses data of yearly average temperature and humidity under rainy conditions that were recorded for a period of 10 years, from 2004 until 2014.

3. PV model for monitoring weather and identifying dust accumulation on PV surface

Fig. 3 shows the PV power monitoring system designed in this paper. The inputs to the module are as follows. Firstly, data of PV parameters were input in accordance with the type of PV tested and its accompanying data sheet. Secondly, information pertaining to geographical location (such as latitude and longitude) was input, together with local annual average temperature and humidity under rainy conditions. Thirdly, instrumentation for conducting actual measurements was input: current sensor, voltage sensor, temperature sensor, and humidity sensor. The module also contains a real time clock to determine the time of sunset and sunrise and position of sun.

The prototype module for monitoring weather and dust accumulation is shown in Fig. 4. This prototype uses TFT LCD to store the tested PV parameters and geographical data.

Identification of power reduction caused by dust accumulation and weather is described in the flowchart presented in Fig. 5.

The simple rule-based model used to determine rainfall conditions compares annual average temperature and humidity under rainy conditions with actual temperature and humidity, as shown

Table 2
PV parameters.

Model	SL100CE-18M
Power warranty	10 Years at 90% Output Power, 25 Years at 85% Output Power
Electrical data at STC	
Maximum power (P_{max})	100 Wp
Voltage at maximum power (V_{mpp})	17.49 V
Current at maximum power (I_{mpp})	5.71 A
Open circuit voltage (V_{oc})	21.67 V
Short circuit current (I_{sc})	6.11 A
Panel efficiency	12.02%
Power tolerance(positive)	+5%
Power tolerance(negative)	−5%
Standard test conditions (STC): air mass AM 1.5, irradiance 1000 W/m^2, cell temperature 25 °C	
Thermal ratings	
Operating temperature range	−45–85 °C
Temperature coefficient of P_{max}	−0.47%/°C
Temperature coefficient of V_{oc}	−0.38%/°C
Temperature coefficient of I_{sc}	0.04%/°C

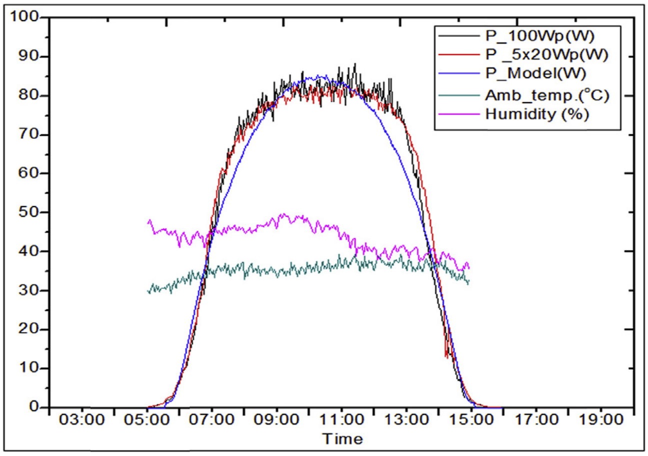


Fig. 6. Validation of model using field measurement test.

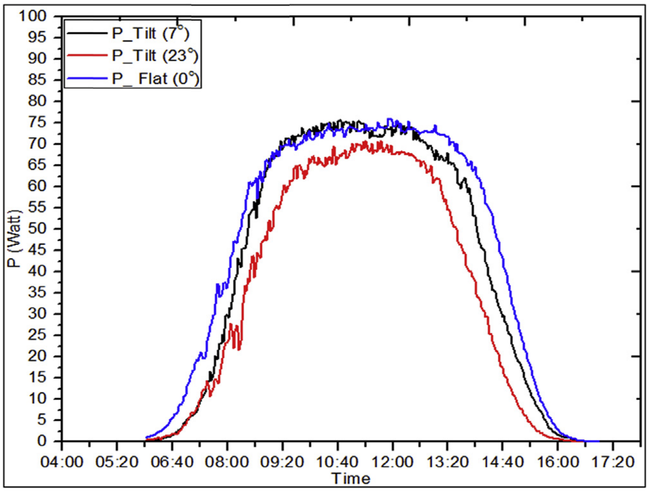


Fig. 7. Comparison of PV output power using different tilt angles.

in Table 1. The annual average temperature in Surabaya under rainy conditions is 29.15 °C, and humidity under rainy conditions is 72.92%. It is of note that this rule-based model is valid only from 08.00 to 15.00 (times before and after these times are known as "local obstacles"), and thus the reduction of PV output power caused by rainfall can only be identified between 08.00 and 15.00.

Data pertaining to PV parameters, geographical position, temperature, date, and time were processed using a 32bit microcontroller system to predict the PV output power from sunrise to sunset via use of the formulae described in Equations (1)–(8) . The prediction of PV output power within a whole day from sunrise until sunset was then stored on a micro SD Card every two minutes using CSV format. In addition to storing predictions of PV output power on a micro SD Card, real output power, ambient temperature, and humidity were also stored on the same micro SD Card every two minutes.

It is note that periodic recording time used is flexible and can be modified as needed. Real PV output power is calculated by measuring the existing PV current and voltage. The recommended minimum PV output power (P threshold) is then calculated at 80% of the PV output power predicted by the model; this value is assumed to be the maximum derating factor of the PV. Field tested PV parameters are given in Table 2.

4. Results and discussion

The PV model with the microcontroller system was validated by comparing results of PV output predictions with results of field measurements, using two PV modules in parallel, a single PV 100 Wp and 5 × 20 Wp, as shown in Fig. 6 (where results of field measurement tests from both the PV 100 Wp and 5 × 20 Wp are also shown). The outputs are very close to those of predicted power determined by the model, but the model results have an average deviation error of 3.6%. In this respect, the model is validated for predicting PV power output.

A field test to determine the amount of decrease in PV output power caused by dust accumulation was conducted in Surabaya during the dry season and the beginning of rainy season from August to November 2014. Monitoring to determine any reduction in PV output power caused by dust accumulation was conducted from sunrise to sunset; these times of which were automatically determined using the sunrise and sunset formula. All data were then stored automatically on a micro SD card.

After validating the model using the two types of PV modules, data were then recorded using different tilt angles, 7° and 23°, and with the modules lying in a flat position. The results are shown in Fig. 7, where it is evident that the output power is higher when the module is in a flat position than in either of the tilted positions. This is related to the sun declination angle of around 7° south of the equator line, which is very close to the latitude of Surabaya, which is 7.2361°. These results show that all tests should be performed using flat PV conditions.

The first measurement results of PV output power for a clean surface are shown in Fig. 8. These data were then used as a reference for clean surface conditions. The experiment for dust accumulation shown in Fig. 8 was performed by exposing the PV module to direct weather on the third floor in the Politeknik Elektronika Negeri building in Surabaya, which is located at a longitude of 112.533° and latitude of 7.2361°.

After conducting tests using the clean surface PV, dust was allowed to accumulate for a period of one week prior to monitoring using dust accumulation, the results of which are shown in Fig. 9. It is evident that PV output power begins to decrease slightly by around 2.05% compared to the clean condition, and decreases by around 1.04% compared to the model. However, the decrease in power output in relation to dust is very low, and thus the results are difficult to determine.

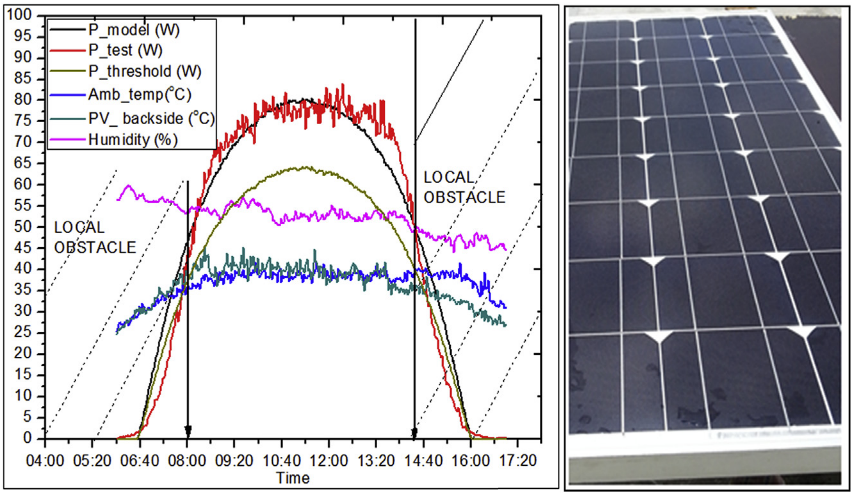


Fig. 8. Photovolatic output power from clean surface, recorded in final week of August 2014.

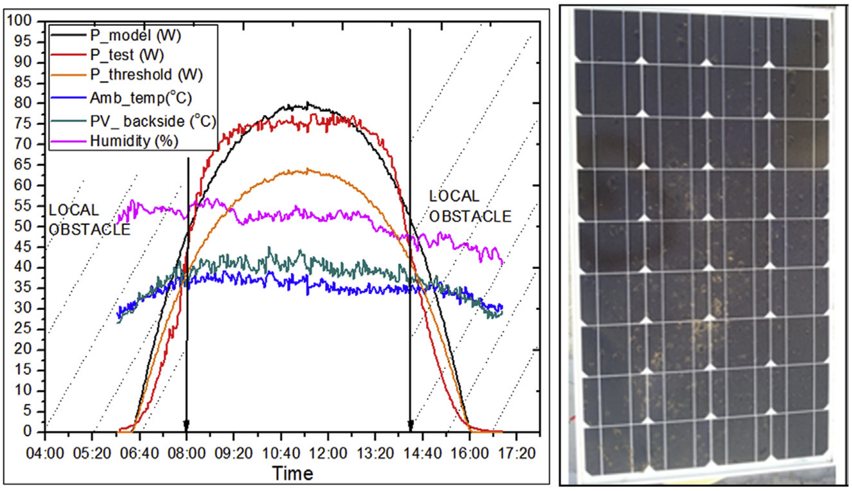


Fig. 9. PV output power after one week of dust accumulation in the first week of September 2014.

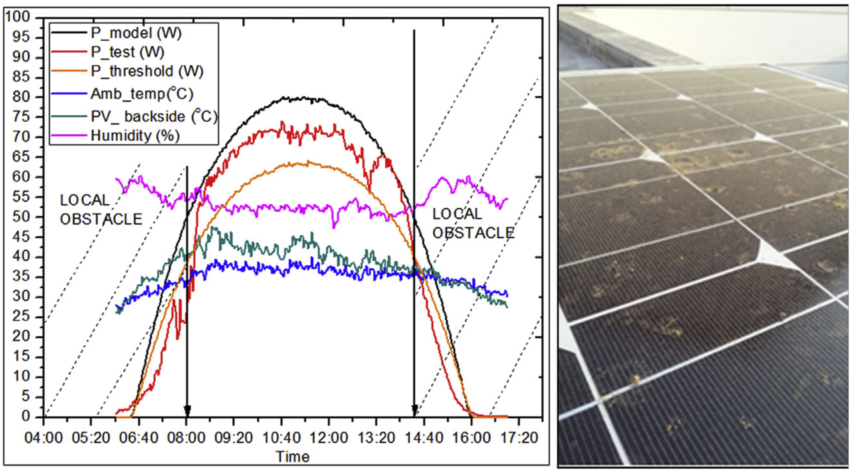


Fig. 10. PV output power after two weeks of dust accumulation, recorded in September 2014.

Fig. 10 shows the results of monitoring PV power reduction after two weeks of dust accumulation on the surface of the PV, when the dust was clearly visible and evidently led to a significant decrease in output power. The power reduction after two weeks of exposure

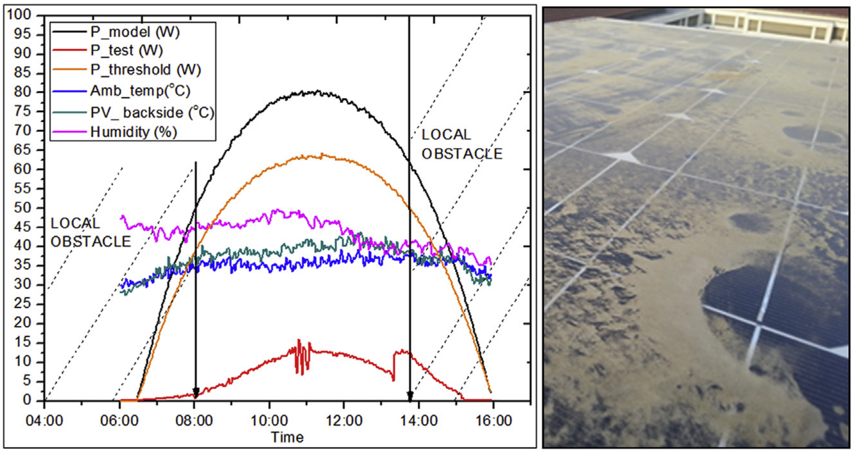


Fig. 11. PV output power after four weeks of dust accumulation, recorded in the third week of September 2014.

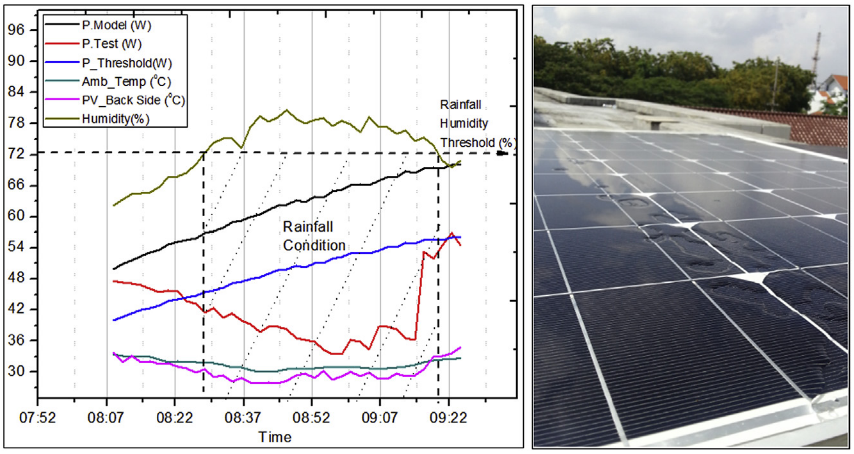


Fig. 12. PV output power during rainfall condition, recorded in October 2014.

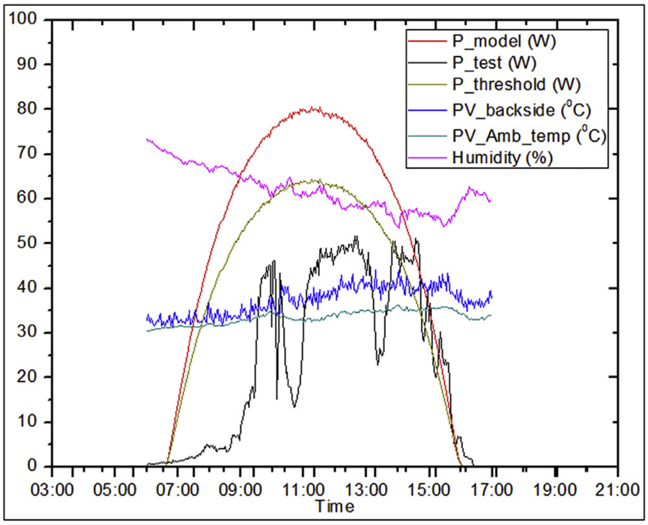


Fig. 13. PV output power in cloudy conditions, recorded during November 2014.

caused by the dust accumulation was around 10.8% compared to the clean surface condition, and it decreased by 9.25% compared to the model. The PV surface was defined as having a “dusty condition” because there was a decrease in the power output of around 10%, with an average relative humidity of 52.24%, and average ambient temperature of 36.89 °C. It is known that dust and particles produced by traffic pollution, construction activities, and the combustion of fossil fuels build up quickly on the solar cells, and can reduce efficiency by 20%. In addition, during the dry season a very thin layer of dust can reduce solar power conversion by 40% [31,32].

During the fourth week there was a short period of drizzle. In addition, during the two week period after the previous monitoring (which was conducted after two weeks of dust accumulation), extra dust had accumulated on the PV surface, causing an increased concentration of dust on the PV surface, which thus caused a very significant reduction in power of 87.29% and a decrease of 87.29% compared to the model. The condition of the PV surface was determined as being “dusty” because of the decreased power output of around 87%, an average relative humidity of 44.77%, and average ambient temperature of 36.11 °C. Fig. 11 shows results of monitoring PV power reduction after four weeks.

We then monitored the reduction in PV power in relation to rainfall conditions. A clean surface PV was used for this, and Fig. 12 shows the results. Rainfall causes high humidity and thus the PV output power is very low. The power reduction in this test was around 43.03% compared to the clean surface under sunny conditions, and it was decreased by 41.85% compared to the model. From these data, it can be seen that a reduction in PV power reduction is caused by rainfall because the decrease in output power was more than 40% with an average relative humidity of 76.32%, and average ambient temperature of 28.97 °C.

In the final experiment, we monitored the reduction in PV power in relation to cloudy conditions. A clean surface PV was used in this experiment, and Fig. 13 shows the results. PV output power was unstable in these conditions, and there was high humidity and a low ambient temperature. A power reduction of around 53.69% was recorded in comparison with results using a clean surface under sunny conditions, and a decrease of 48.75% compared to the model. From these data, it can be seen that PV power reduction is caused by cloudy conditions because there is a decrease in output power of more than 45% with an average relative humidity of 60.45%, and an average ambient temperature of 34.06 °C. In fact, the PV module performance decreases in conditions of soft shade (such as cloud), or when there is dust or smog in the atmosphere, as this causes a reduction in solar irradiance absorbed by the solar cells. This effect is exacerbated in conditions of hard shade, for example when surface soiling blocks solar irradiance [33].

5. Conclusions

In this paper, experimental investigations were conducted to study the effect of dust accumulation and weather conditions on PV output power in Surabaya, Indonesia. A measurement system was developed for these investigations, using a simple rule-based model, to determine different environmental conditions. The experiments demonstrated a significant decrease in PV output power in relation to dust accumulation during a long period of dry conditions. Results of experiments show that dust accumulation after two weeks' exposure in the dry season caused a PV output power reduction of 10.8%. Two different weather conditions were considered to analyze the effect of local weather conditions on PV output power, rainy and cloudy conditions. Results from the experiment under a rainy condition showed that PV output power decreased by more than 40% when there was an average relative humidity of 76.32%, whereas during cloudy conditions the decrease in output power was more than 45% when there was an average relative humidity of 60.45%. Use of the rule-based model to identify weather conditions was thus validated for rainy and dusty conditions; however it was proficient in identifying cloudy conditions.

This study reveals that dust accumulation and weather conditions have a significant effect on PV output power reduction during the dry season in the city in this study. However, further research is required in relation to issues of PV generated power losses due to dust deposition and weather conditions, and suggestions for this are as follows:

- Comprehensive studies involving rule-based modeling are required for identifying cloudy conditions in the measurement system.
- The need for monitoring and analysis of environmental effects (particularly dust accumulation and regional climatic parameters), on PV panel performance over long time periods.
- An effective and efficient cleaning system and implementation procedure needs to be developed, based on accurate identification of dust deposition and weather conditions during the dry season.

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